A study of wave forces on offshore platform by direct CFD and Morison equation

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Outline

Motivation

- Development of a "Cyber Wind Facility" capable of predicting transient loads and motions of an offshore turbine and floating platform operating in marine atmospheric boundary layer and ocean waves
  - Hydrodynamics and mooring–line dynamics are key considerations for this problem
- Current state-of-the-art engineering tools are based upon semi-empirical time-domain methods (e.g., Cummins equation)
  - Examples include: NREL's Hydrodyn, OrcaFlex, ANSYS AQWA
  - These models use various theories for radiation, diffraction, hydrostatics, and viscous effects.
  - Morison's equation is commonly used for damping and inertia forces due to wave excitation.
- Some floating platforms have complex underwater geometry (e.g., OC4 Semi-submersible), which precludes the use of theoretical or historical data for drag, inertia, damping, added mass, etc.

Objective of current study

- Perform multi-phase RANS simulations of a fixed platform in waves (i.e., the diffraction-wave problem).
  - This is a precursor study prior to undertaking full 6DOF/RANS simulations, including mooring-line models
- Compare CFD computed wave-excitation forces for OC3 spar-buoy to Morison's equation model (using both CFD-based or experimental coefficients).

Outline

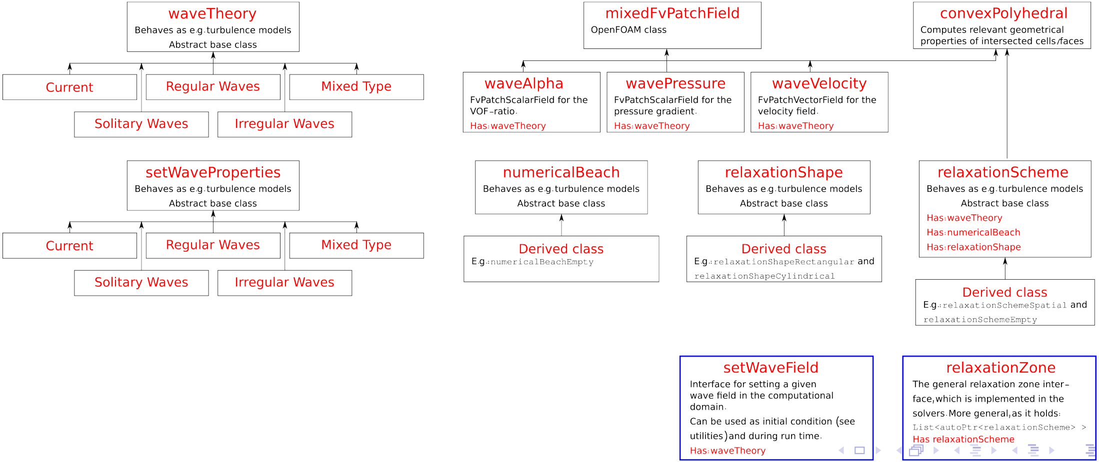
Computational Model

- Tightly–coupled multiphase Navier-Stokes equations and Newton's 6DOF equation-of-motion. Following presentation by A. Dunbar will present details of algorithm.
- Wave generation using the waves2Foam library (Jacobsen et al., 2012).
- Mooring–line forces via catenary–line model.
- Selectable-fidelity model of the wind turbine, including actuator–disk and actuator–line models. ALM model developed by CWF team members, Prof. Schmitz and Pankaj Jha.
- Dynamic meshing using an Elliptic mesh-deformation model with variable stiffness, which maintains near-wall mesh quality (Campbell and Paterson, 2011).

Wave Library: waves2Foam

Library Structure: Waves theories, Boundary conditions, Relaxation techniques, Dictionaries, and Utilities.

`libwaves2Foam.so`



Wave Library: waves2Foam

- Common wave theories are implemented in waves2Foam
  - Potential current
  - Regular waves: Stokes 1st, 2nd and 5th order theory
  - Solitary wave
  - Irregular waves
- Boundary conditions apply wave theory to velocity, pressure, and volume-fraction fields.
- Relaxation zones provide numerical beaches for explicit and implicit damping of waves to control wave reflections
- Utilities are provided, e.g., `setWaveField` is similar to `setFields` for prescribing initial wave field to velocity and alpha fields.

Outline

Floating platform geometry

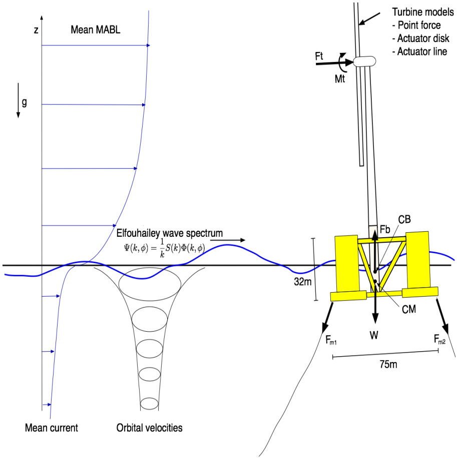


Figure : Schematics of Semi-Submersible platform with wind turbine in ocean waves and currents(Popko, et al., 2012)

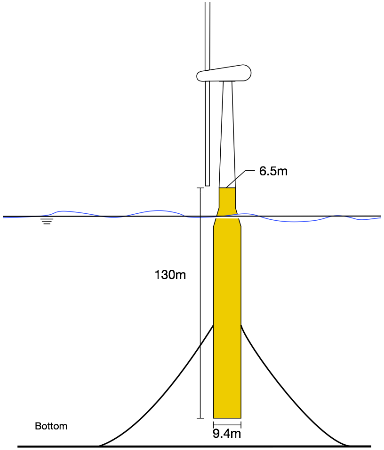


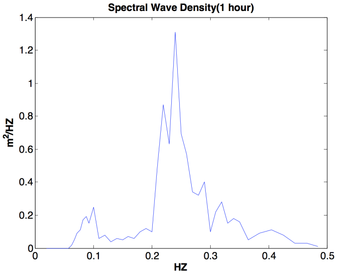
Figure : Schematics of OC3-Hywind spar buoy with wind turbine in ocean waves and currents (Jonkman, 2010)

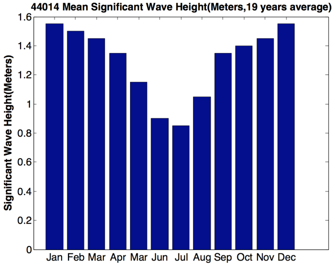
Outline

Flow conditions

Statistical data from National Data Buoy Center(NDBC)

- Close to research area of Virginia Offshore Wind Technology Advancement Project(VOWTAP).
- Real time data updated every 1 hour
- Historical data in the last two decades including
  - Standard meteorological data
  - Continuous winds data
  - Spectral wave data
  - Ocean current data

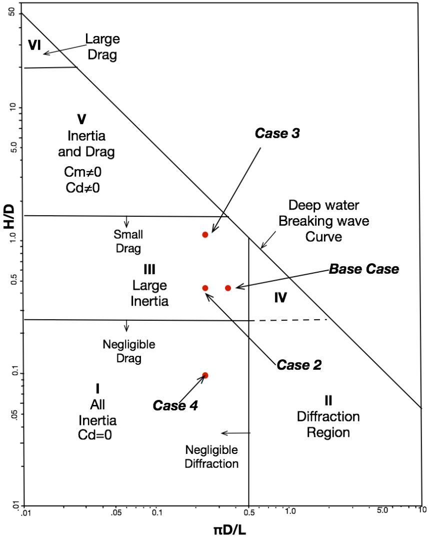




Flow conditions

Chart (Chakrabarti 1987) with summary of four cases and dominant physics.
First-order Stokes' wave:

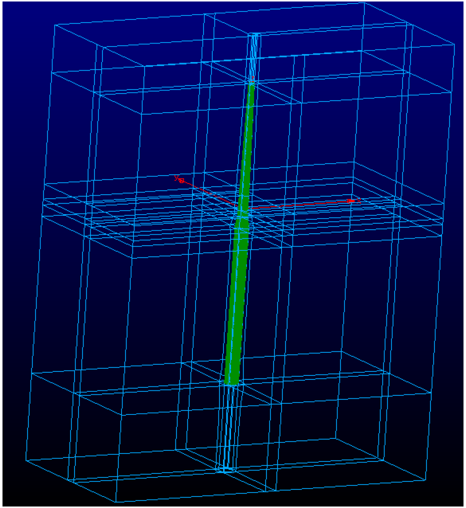
- Base case: H=3m, L=60m
- Case 2: H=3m, L=90m
- Case 3: H=7m, L=90m
- Case 4: H=0.65m, L=90m



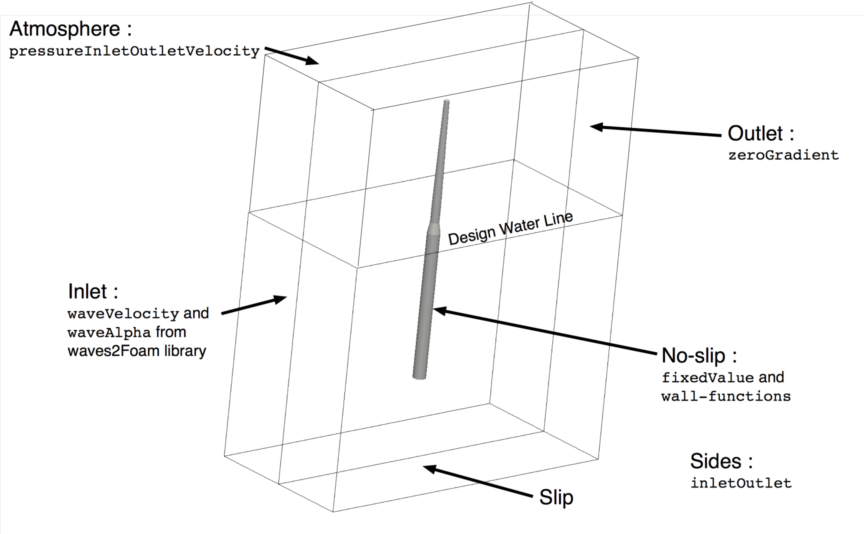
Outline

Meshing and boundary conditions

- Mesh generated using Pointwise.
- Buoy+tower system is very tall: buoy depth of 120m, hub-height of 90m.
- Domain size
  - -120m $\leq$ x $\leq$ 120m
  - -60m $\leq$ y $\leq$ 60m
  - -180m $\leq$ z $\leq$ 120m
- Near-wall resolution: 1cm (very coarse)
- Uniform axial spacing upstream of buoy for resolving waves
- Vertical clustering around DWL - design water line



Meshing and boundary conditions



Computational parameters

- Finite volume schemes
  - limited schemes used to improve stability
  - `cellLimited Gauss linear` for gradSchemes of `U` and `alpha1`
  - Convection schemes used in `divSchemes` sub-dictionary
    - `Gauss linearUpwindV` for momentum equation
    - `Gauss vanLeer` for VOF equation
    - `Gauss interfaceCompression` for interface sharpening
    - `Gauss upwind` for turbulence models
- Finite volume solvers
  - `GAMG` with the `DIC` smoother for pressure-Poisson equation
  - `PBiCG` for all other equations
- PISO algorithm control
  - nCorrectors 3;
  - nNonOrthogonalCorrectors 1;
  - nAlphaCorr 1;
  - nAlphaSubCycles 1;
  - cAlpha 1;

Outline

High-Performance Computing Resources

- Advanced Research Computing (ARC) at Virginia Tech
  - BlueRidge: 318-node Cray CS-300 cluster, each node is outfitted with two octa-core Intel Sandy Bridge CPUs and 64GB memory.
  - Hokiespeed: GPU-accelerated cluster with 204 nodes. Each nodes has 24GB memory, two six-core Xeon E5645 CPUs with two NVIDIA M2025/C2050 GPU.
  - Each user can request up to 1024 cores on Blueridge and 384 cores on Hokiespeed.
  - Maximum run time in normal queue is 144 hours and 72 hours respectively.
- We currently use foam-extend-3.0. Have used OpenFOAM 2.2 and 2.3, but recent bugs have caused concern in using these versions.
- For mesh of 5M cells, execution time less than 3 hours on 96 processors for 120 seconds of physical time (approx 10-15 wave encounters).

Outline

Free-surface wave-elevation contours

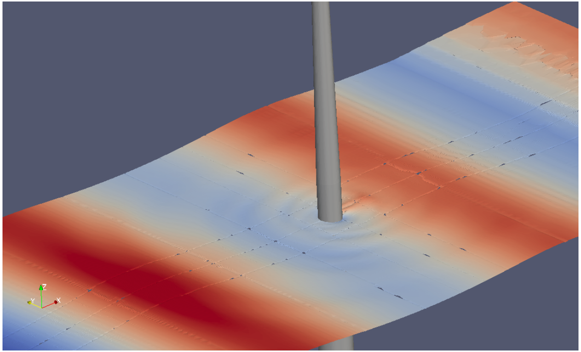


Figure : Wave elevation on free surface (H=7m, L=90m)

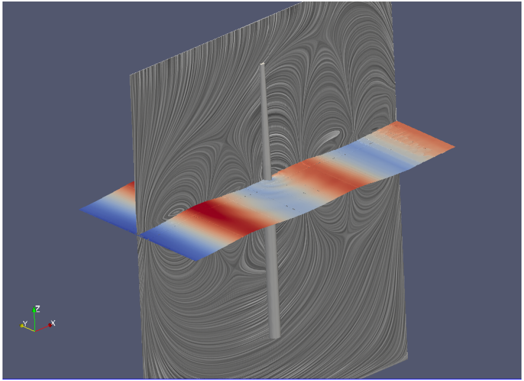


Figure : Wave elevation on free surface with wave-induced circulations in y–plane (H=7m, L=90m)

Unsteady velocity field vs. depth

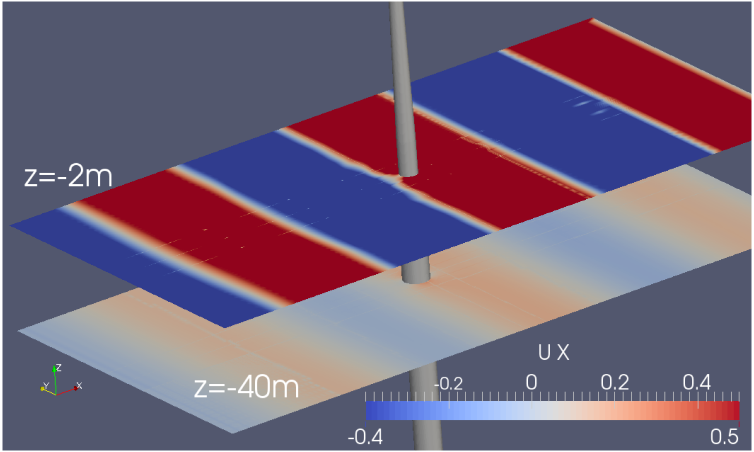
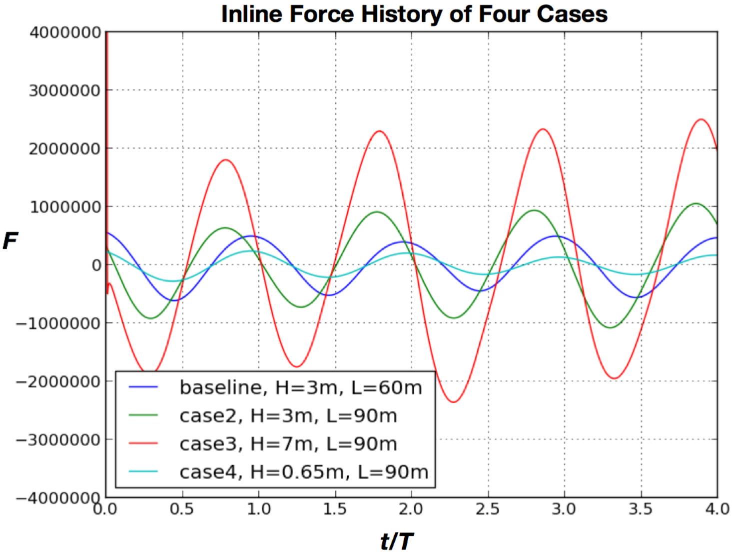


Figure : Variation of flow velocity in x–direction with depth (H=7m, L=90m)

For reference, velocity field of 1st-order Stokes wave

$$u(x,t) = \omega A \exp^{kz} \cos(kx - \omega t)$$
$$w(x,t) = \omega A \exp^{kz} \sin(kx - \omega t)$$

Unsteady inline force



Outline

Wave force theory

Morison's equation for circular cylinder

$$F = \frac{\pi}{4} C_m \rho D^2 \frac{\partial U}{\partial t} + \frac{1}{2} C_d \rho D U \mid U \mid$$

$$U = U_m \sin(\omega t)$$

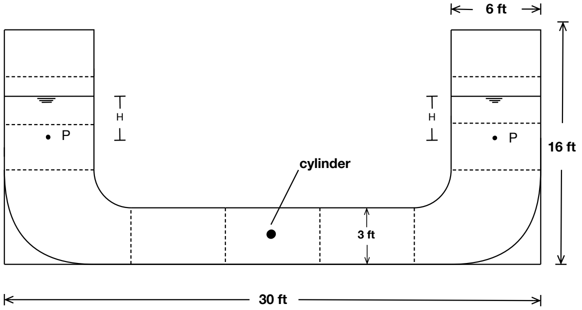
- F is the inline force; C_m and C_d are the inertial and drag coefficient
- C_m and C_d are functions of Keulegan-Carpenter number $K = U_m T / D$ and Reynods number $Re = U_m D/\nu$
- It's a empirical approach, a vast range of experimental data on C_m and C_d is available from numerous lab and field tests
- Provides acceptable and reliable prediction of wave force on many offshore structures.

Experimental data (Sarpkaya, 1976)

Sarpkaya (1976) conducted a series of experiments in a U-shape water tunnel to study the hydrodynamic force on different size cylinders in various flow conditions

- Period $T = 5.5s$
- 7 cylinders with diameters ranging from 2 to 6.5 inches were used

U-Shape water tunnel (Sarpkaya 1976)



Experimental data (Sarpkaya, 1976)

- Frequency parameter $\beta = Re/K = \frac{D^2}{\nu T}$
- For small K, C_m converges to 2
- C_m drops to minimum and C_d reaches maximum at $K \approx 15$

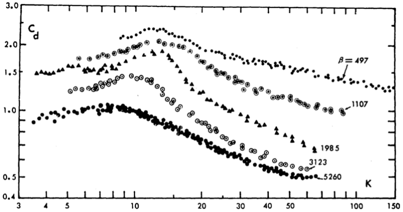


Figure : C_d versus K for various values of β

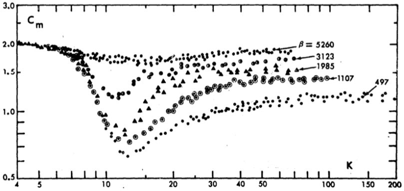


Figure : C_m versus K for various values of β

Experimental data (Sarpkaya, 1976)

- Sarpkaya(1976) also studied the force on cylinders at high Reynolds number.
- We can observe from the figures that at high Re, C_m approaches 1.8 and C_d approaches 0.65 at various values of K.

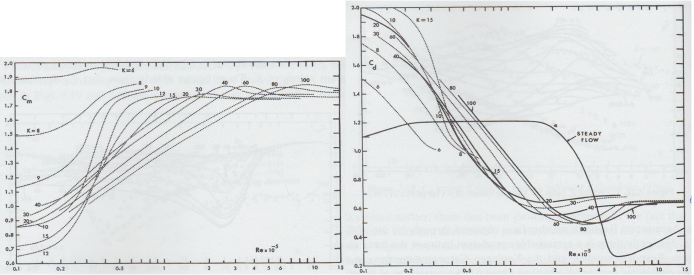
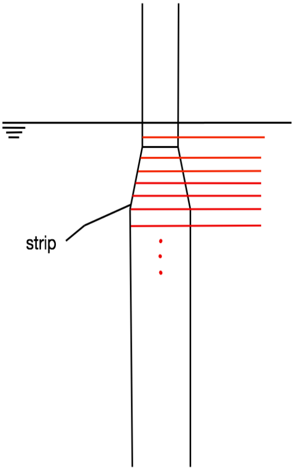


Figure : C_m(left) and C_d(right) versus Re for various values of K

Application to 3D using Strip Theory I



- Water particle velocity is derived from linear wave theory
- Reynolds number along the vertical length of the pile ranges from 10^7 near free surface to 10^5 at wave base.
- We assume $C_m = 1.8$ and $C_d = 0.65$

Application to 3D using Strip Theory II

- By assuming linear theory, we have the ratio between inertial and drag force:

$$\frac{f_{D_{max}}}{f_{I_{max}}} = \frac{C_d}{\pi^2 C_M} K \approx 0.036K$$

- For wave amplitude of 1.5m in the base case, even for highest $K \approx 1.5$, we have $\frac{f_{D_{max}}}{f_{I_{max}}} = 5.3\%$
- Drag force is negligible compared with inertial force.

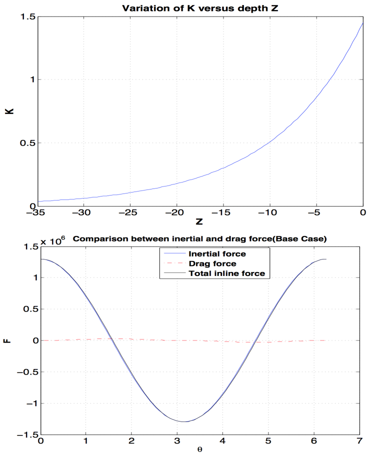


Figure : Inline force history of the base case in one cycle

Comparison of CFD and Strip Theory

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Average peak force:

	Base	Case 2	Case 3	Case 4
CFD	5e5	1e6	2.5e6	2e5
Morison's equation	1.25e6	1.4e6	3.3e6	3.1e5

Two possible reasons for the difference:

- Lack of full–scale coefficients and the uncertainty of extrapolation from model scale
- Numerical uncertainties in CFD and lack of grid–dependence study

Prognosis for accurate prediction using Morison's equation for complex geometry is poor

Outline

Conclusions

- The “Cyber-Wind Facility” Hydrodynamics Module has been used for several different applications.
  - 2D simulation of KC problem for Morrison’s equation coefficients *at model scale for comparison to Sarpkaya (1976)* [not discussed].
  - Simulation of OC3 spar-buoy in waves using `interFoam` and `waves2Foam`. Conditions set to H_s typical for future offshore-wind-plant near the coast of Virginia.
- Diffraction-wave loads (i.e., fixed platform) compared to strip-wise application of Morison’s equation. Agreement is poor.
- Hypothesis for discrepancy is that full-scale coefficients are unknown, and CFD accuracy not yet assessed using domain–size, and time–step and grid refinement studies.
- Use of robust HPC resources at VT-ARC give good turn-around. Many cases can be simulated in 24-hour period.

Future Work

- Re-mesh for larger domain which includes rotor disc.
- Compute Morison's equation coefficients at full–scale conditions, and quantify 3D and scale effects.
- Test and debug mooring-line model
- Collaborate with CWF team members
  - Use A. Dunbar's tightly coupled 6DOF/RANS solver
  - Incorporate S. Schmitz and P. Jha ALM for turbine forces
- Extend `waves2Foam` for directional spectrum and short-crested wave model (e.g., Elfouhailey, et al., 1997)
- Write and defend PhD dissertation (December 2015)